General Training On Methodologies For Geological Disposal in North America
IAEA Network of Centers of Excellence

Natural and Man-made Natural Barriers:
Canadian Granite

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Natural Barriers in the Canadian Concept

Low-permeability plutonic rock of the Canadian Shield

- **Sparsely fractured**
- **Tectonically stable**

Sparsely fractured granite permeability ~10^{-20} m^2.
Precambrian rock >2.5 billion years old.
Most recent tectonic event >100 million years.
Very low hydraulic gradients.

Natural Barriers in the Canadian Concept

- **Only feasible way for radionuclides to reach the biosphere is by dissolution in water and subsequent short-circuiting to a water-bearing fracture zone (fault)**
- **Natural crystalline rock barrier is intended to prevent this**

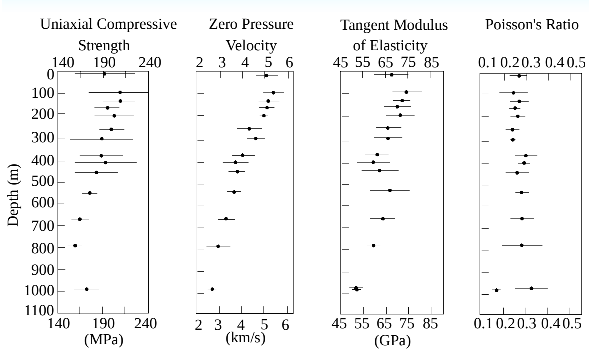
Natural Rock Barrier at URL

URL Rock Properties

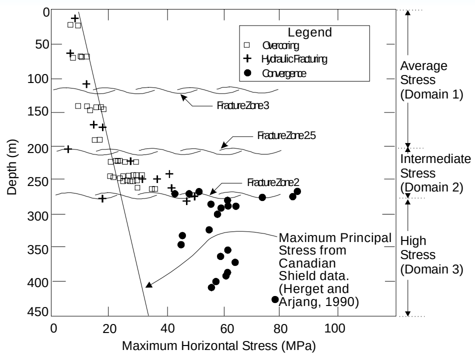
In laboratory testing of samples obtained from borehole core samples, the values of the following rock properties all decreased with depth:

- Uniaxial compressive strength
- Acoustic velocity
- Modulus of Elasticity
- Poisson’s ratio

Laboratory Rock Properties with URL Depth



In-Situ Stress Magnitudes at URL



URL Rock Properties

- **Initial characterization studies indicated that the rock at depth was weaker than shallower rock (mainly due to microcracking).**
- **Deep *in-situ* stress determinations indicated that stress magnitudes increased significantly with depth.**

Conclusion

- **Damage resulting from sample removal from high *in-situ* rock stress environments was causing the apparent degradation in rock properties with depth. Rock properties determined through laboratory tests are not always representative of *in-situ* values.**

Diffusion

- **Diffusion affected by sample disturbance**
- **Diffusion coefficients determined in the laboratory are higher than those determined *in-situ* due to sample disturbance.**

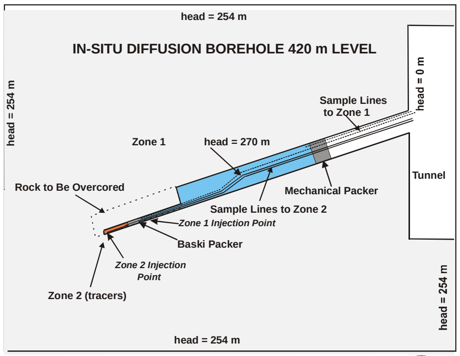
Evidence Of Sample Disturbance

- Increased estimated sample porosity, diffusivity and permeability at higher stress environments (σ_1: 30, 54, 60 MPa)
- Laboratory estimated **permeabilities** and **diffusivities** appear significantly higher than the *in-situ* values
- The rock sampling process appears to increase permeability and diffusivity by creating an increase in connected porosity, as well as modifying the pore geometry

Effective Diffusion Coefficients (m^2/s)

	240-m Level	300-m Level	420-m Level
HTO	8.1×10^{-13}	1.8×10^{-12}	1.9×10^{-12}
I	2.8×10^{-13}	1.1×10^{-12}	1.2×10^{-12}
Li	$>3 \times 10^{-13}$	1×10^{-12}	8×10^{-13}
Rb	$>2 \times 10^{-15}$	1.4×10^{-12}	1.2×10^{-12}
Uranine	1×10^{-13}	8×10^{-13}	4.3×10^{-12}

Diffusion Borehole Installation

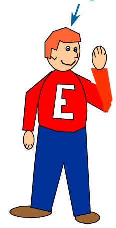


Other Natural Barriers

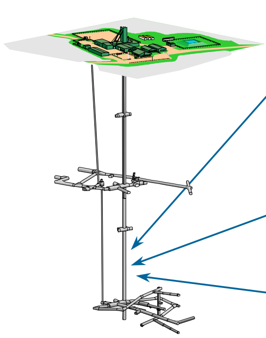
- Other barriers to radionuclide release include minerals and mineral fracture infillings that can sorb and/or retard radionuclides released from waste containers
- URL research demonstrated that the in-situ sorption rates are considerably greater than laboratory determined values, primarily due to the reducing nature of the groundwaters

Welcome to the URL

URL Engineer



Travelling to the 420-Level You May Say:



"There are no fractures when I get way down here!"

"I can see that the horizontal stress is 60 MPa!"

"What a great place to learn about rock fracturing!"

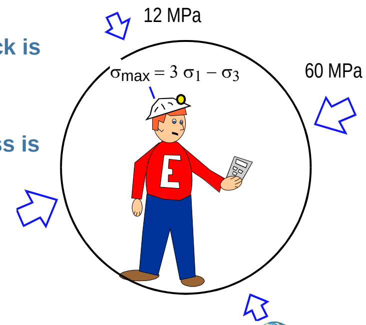
In-Situ Rock Strength

The Mine-by Experiment

The unconfined strength of the rock is 210 MPa

The maximum compressive stress is 168 MPa

In theory, the rock won't break



In-Situ Rock Strength

The Mine-by Experiment

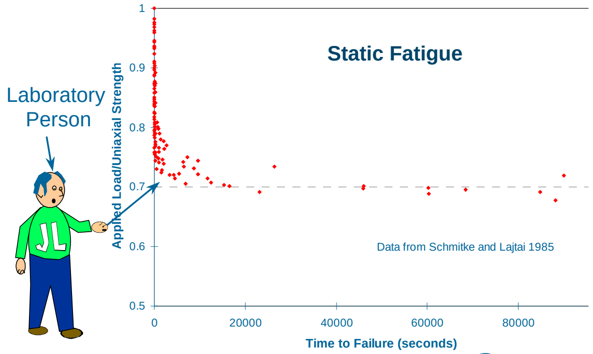
But it did break

In-Situ Rock Strength

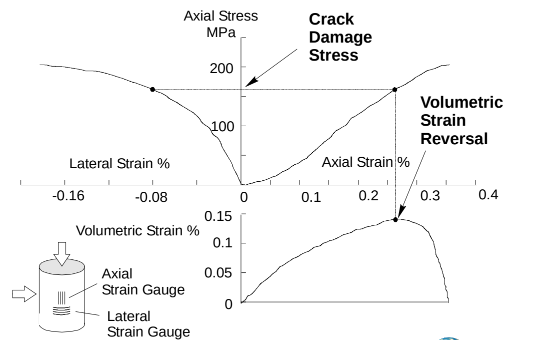
Analysing various excavations at the URL we conclude that the *in-situ* rock strength is only about half the unconfined strength from the laboratory

"Why is the strength so low?"

Long-term Rock Strength



Volumetric Strain Reversal & Long-term Strength



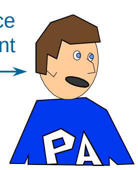
Engineering and Performance Assessment

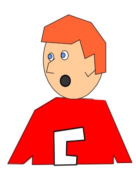
"Can you tell me the thickness of the zone of damaged rock, its hydraulic conductivity and longitudinal dispersivity?"

"GAAK!"

"But you don't understand ..."

Performance Assessment Person →



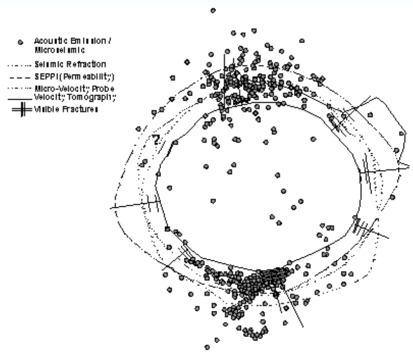


How Large is the Zone of Damaged Rock?

Geophysics Person

- Acoustic emission and microseismic source locations
- Acoustic velocity measurements
- Borehole logging
- Refraction surveys

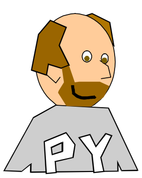
Determining Excavation Damage



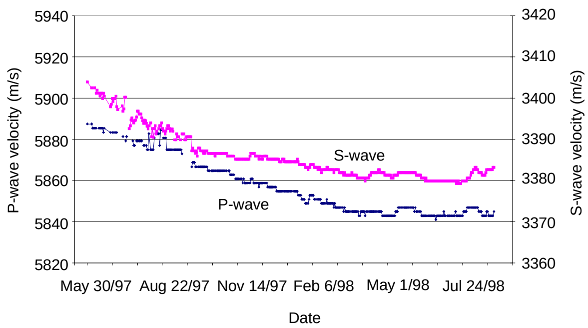
Excavation Damage Zone Characterization

"We now have a set of tools that can tell us the extent of damage and the relative severity of the damage in the EDZ."

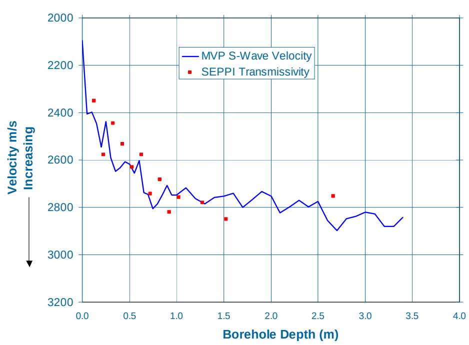
"We can see that microcracking is still occurring in granite one year after excavation."



Acoustic Velocities vs. Time

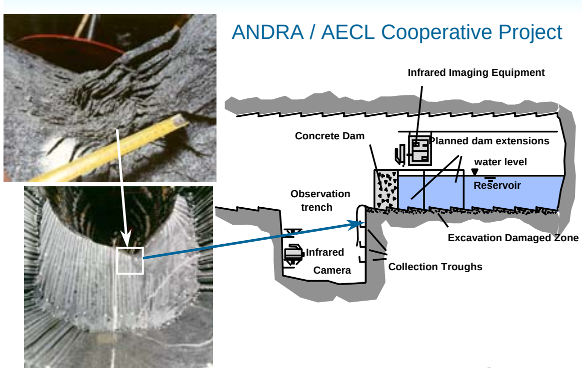


As Velocity Decreases, Permeability Increases



Connected Permeability Test

ANDRA / AECL Cooperative Project



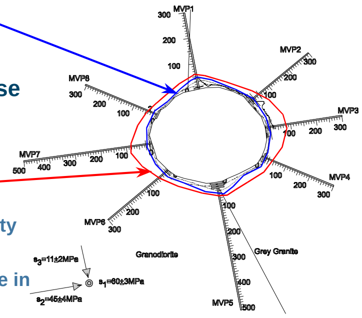
Inner and Outer Damage Zones

Inner Damage Zone

- **Visible fracturing**
- **Permeability increase up to 7 orders of magnitude**

Outer Damage Zone

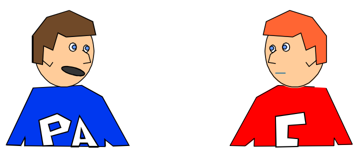
- **Cracking evident from velocity and permeability measurements**
- **10 to 100 times increase in k**



Predicting Rock Damage

"OK, so you can measure the extent of the damaged zone. Can you predict the amount of rock damage at a different location?"

"Hmmmm"



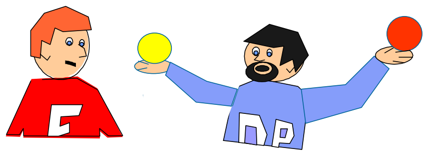
Modelling the Mine-by Experiment

- **Initiation of rock failure on the perimeter of the tunnel was adequately predicted using elastic continuum models.**
- **The linear and non-linear continuum models tested were not capable of simulating the transition from continuum to discontinuum behaviour. The extent and severity of damage could not be predicted.**

Discrete Element Modelling

"Can discrete element models be used to model the process of rock failure?"

"The Particle Flow Code can replicate many of the processes observed in brittle rock. Use of PFC can provide insight into mechanisms of rock failure."



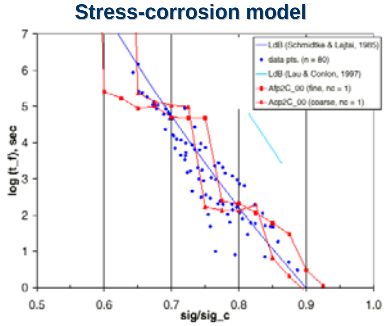
Discrete Element Modeller

Discrete Element Modelling

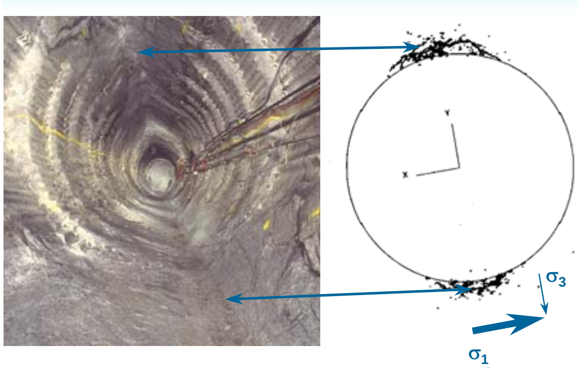
The strength of an inter-particle bond is reduced proportional to applied stress.

Successive time-step iterations result in more bond-breakages.

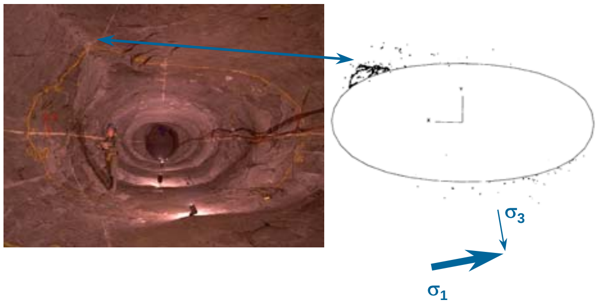
Stress-corrosion model



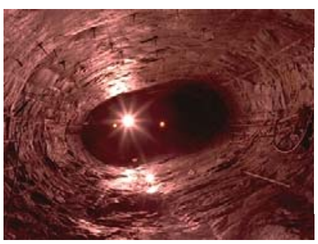
Mine-by Experiment Tunnel Simulation

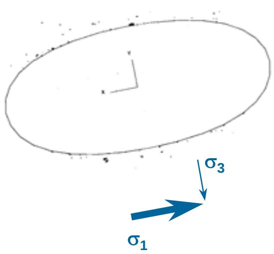


Oval Tunnel with Failure Notch



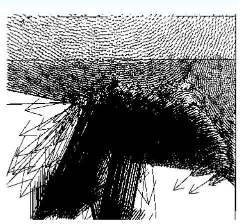
Oval Tunnel with No Failure



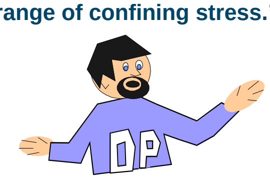


Limitations of PFC

"PFC can simulate many processes that occur during brittle failure."



"But unresolved issues remain in modelling failure at a full range of confining stress."



"Although PFC is a useful, PFC is not a stand-alone design tool."

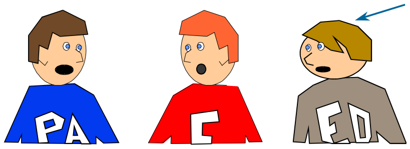
Thermal Considerations

"OK. What if the rock is heated for thousands of years. Wouldn't water expand in the pores of the rock and create new fractures?"

"AAAK"

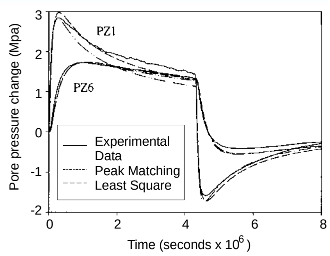
"No problem. We've got it covered."

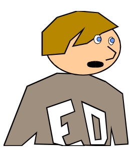
Continuum Mechanics Modeller



Thermoporoelasticity

The theory of thermoporoelasticity is used to predict the magnitude of thermally-induced pore pressures in low porosity rock.





The results from a URL *in-situ* experiment confirmed the thermoporoelastic solutions.

Repository Design

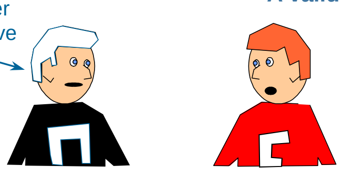
"This is good research, but how does it help me design a repository ? "

"A very good question."

"I also don't think we should rely on only one predictive tool."

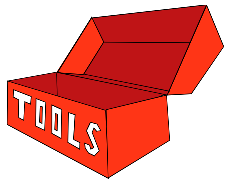
"A valid remark ! "

Waste Owner Representative



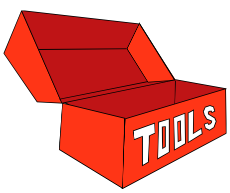
Integrate Everything into a Design Tool Box

- Linear elastic models to predict the onset of failure
- PFC as an indicator of severity of fracturing and whether or not a notch may form
- Long-term laboratory tests to derive stress-corrosion model parameters



Repository Design Tool Box

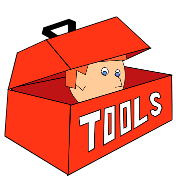
- Geophysical techniques to confirm extent of damage as predicted by numerical design tools



- Thermoporoelastic solutions to determine magnitude of thermally-induced pore pressures and to evaluate potential for thermally-driven pore hydrofracture.

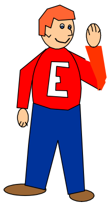
Possible Add-ins to Design Tool Box

- PFC to quantify damage in terms of elastic modulus reduction.
- PFC elastic modulus reduction related to measured *in-situ* changes in acoustic velocity.



- Continuum damage models as complementary tools to discrete element models.

FINIS



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42